Diffusion measurement with transverse beam echoes

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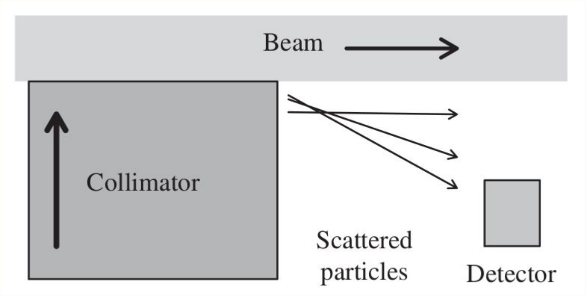
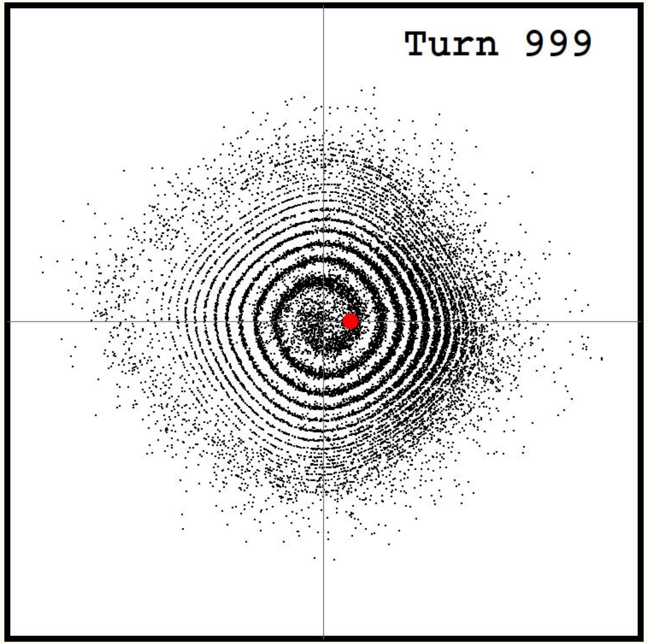
Motivation

- The "intensity frontier"
  - *"Upgrade the Fermilab proton accelerator complex … to provide beams of >1MW"* - HEPAP P5 2014
  - IOTA/ASTA facility at Fermilab
- Mitigation of beam diffusion
  - Resulting from space charge, intrabeam scattering etc.
- Currently measured using collimator scans ("beam scraping")
  - Takes up many hours to complete
- Novel technique: Transverse beam echoes
  - Can cut measurement time down to minutes or less



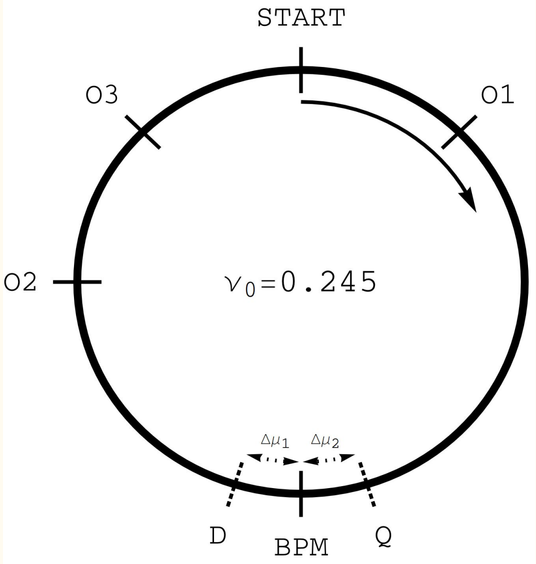
Outline

- Echoes
  - Simulation
  - Theory
- Diffusion
  - Measurement methods
- Pulsed quadrupoles
- Conclusion
  - Future work



A basic echo

- Ring with octupole nonlinearity



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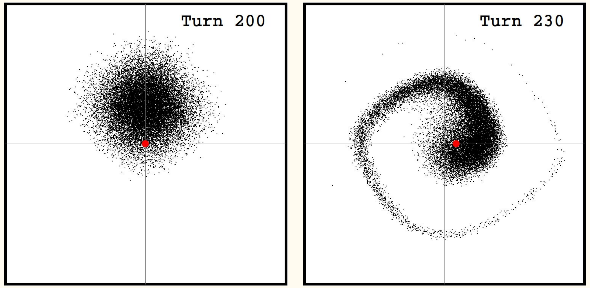
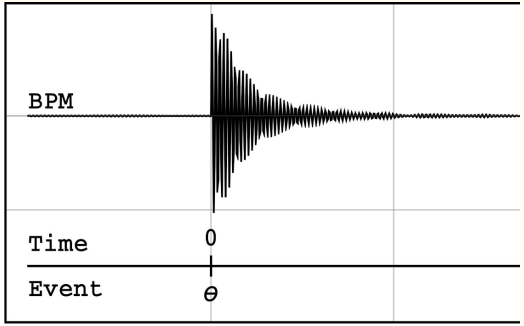


- Ring with octupole nonlinearity
- At t = 0, apply dipole kick θ
    - Phase decoherence due to nonlinearity



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- At t = 0, apply dipole kick θ
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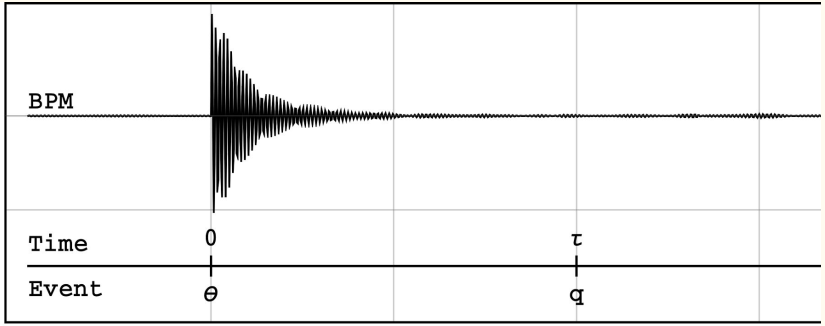
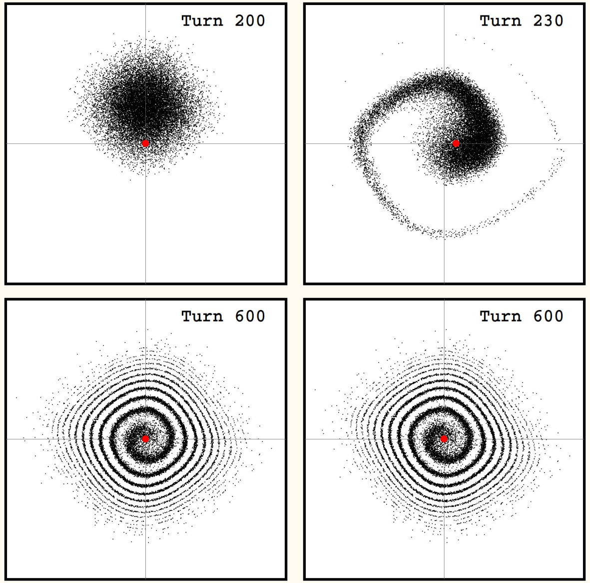
- At t = τ, apply quadrupole kick *q*
    - Recoherence of beam distribution





A basic echo

- Ring with octupole nonlinearity
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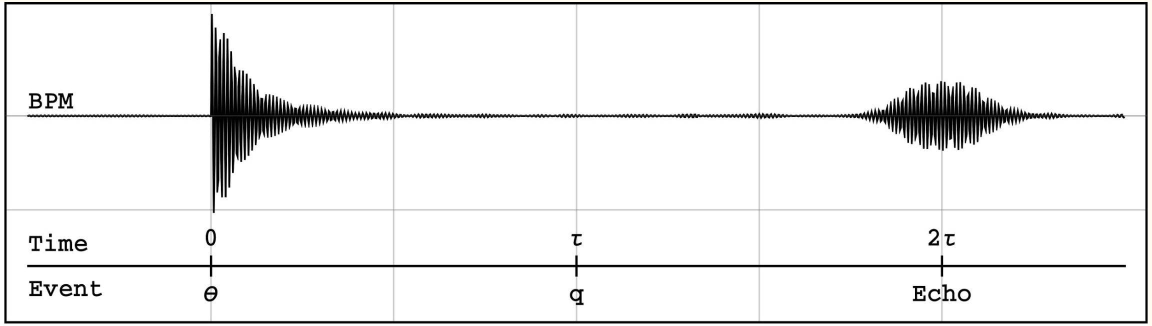
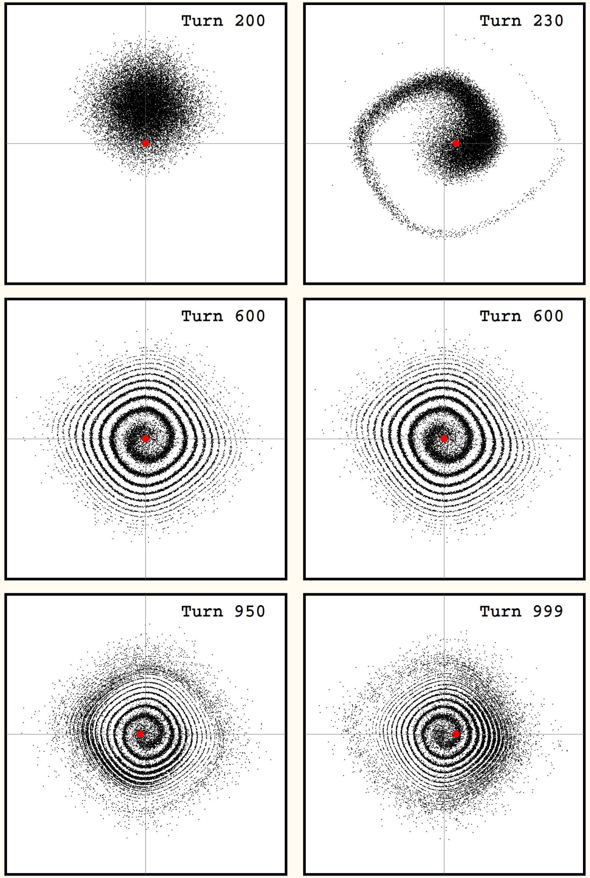
- At t = 2τ, echo signal appears on BPM





Echo amplitude

$$a_0 = \theta q \sqrt{\beta \beta_k} \omega' J_0 \tau$$

- Peak echo amplitude depends on ring and beam parameters
    - Dipole kick [rad] - θ
    - Quad kick strength [1] - q
    - Delay time [s or turns] - τ
    - Betatron functions [m] - β, β_k
    - Detuning [m-rad^{-1}/s] - μ or ω'
    - Initial emittance [m-rad] - J_0

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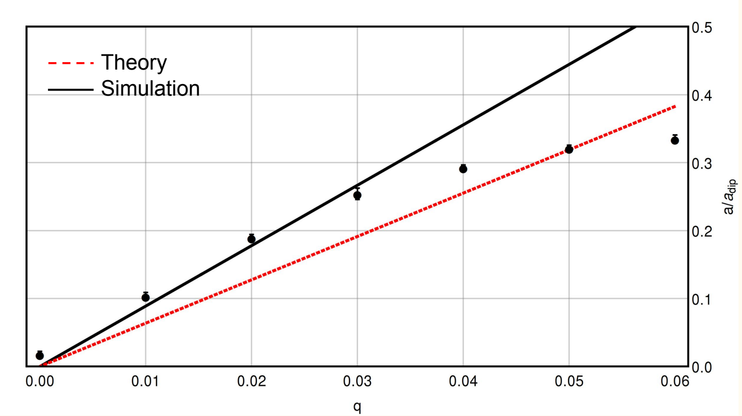

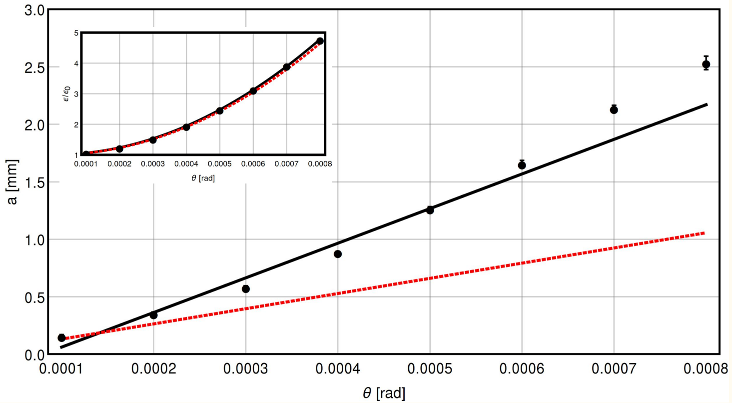

Diffusion (linear)

$$\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial J}\left(D(J)\frac{\partial \psi}{\partial J}\right), \quad \text{where} \quad D(J) = D_0 + D_1\left(\frac{J}{J_0}\right)$$

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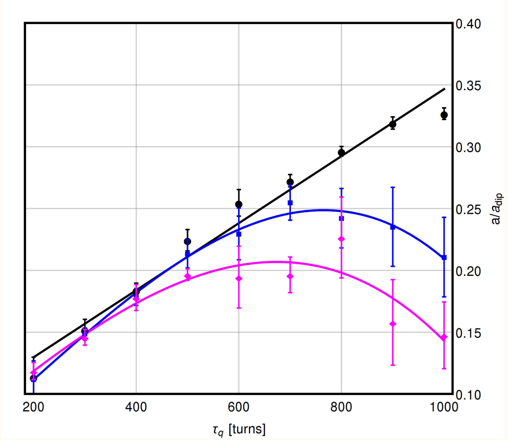
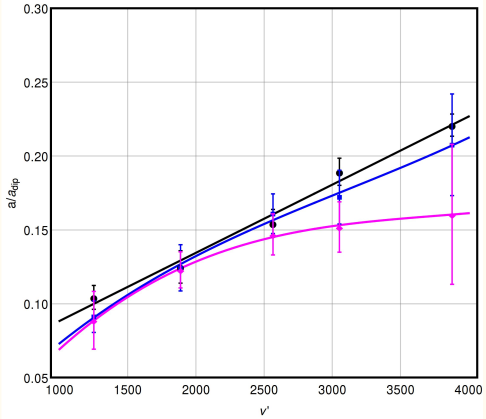
- Alters relationship with τ and ω'





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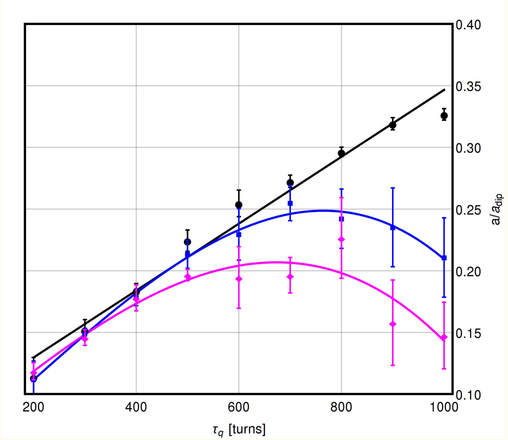
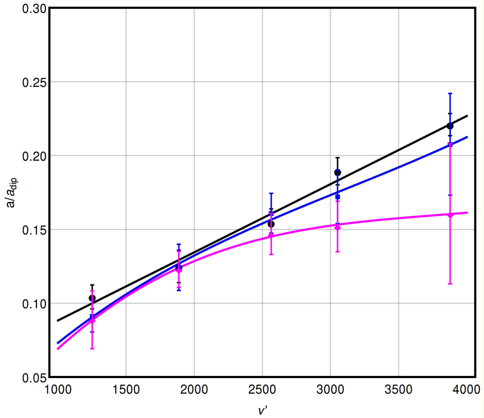


- Attenuates echo amplitude
- Alters relationship with τ and ω'
- Measuring diffusion coefficient
  - Using attenuation factor
  - Using τ_{max} and ω'_{max}
  - Using FWHM of echo signal

$$\tau_{\max} = \left(\frac{16}{3}\omega'^2 D_1\right)^{-1/3}$$

$$\omega'_{\max} = \left(\frac{10}{3}\tau^3 D_1\right)^{-1/2}$$

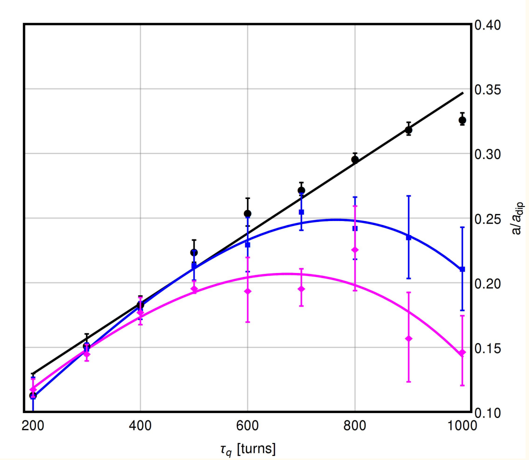


Diffusion measurement with τ_{max}

- We measured τ_{max} of ~700 turns (blue).

$$\tau_{\max} = \left(\frac{16}{3}\omega'^2 D_1\right)^{-1/3}$$

- Working backwards, we find $D_1 \approx 1.5 \times 10^{-18}$ m-rad^2/turn



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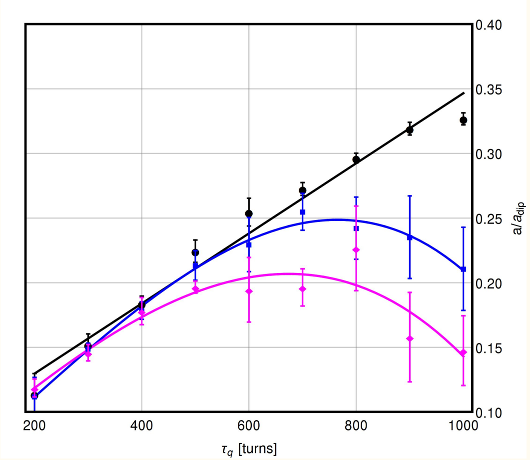
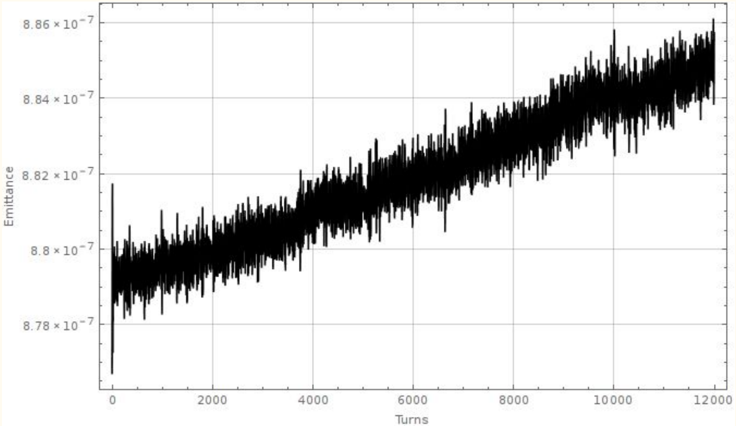
- Independent calculation from tracking emittance growth over time yields $D_1 \approx 1.4 \times 10^{-18}$ m-rad^2/turn

$$D_1 = \pi\epsilon_0 \frac{\mathrm{d}\epsilon}{\mathrm{d}t}$$

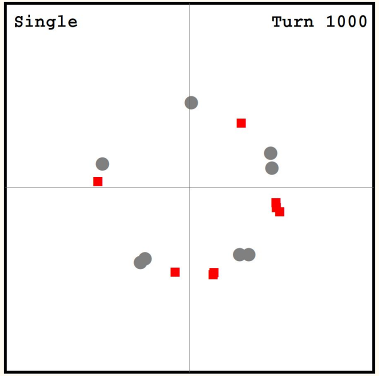
- Self-consistent results

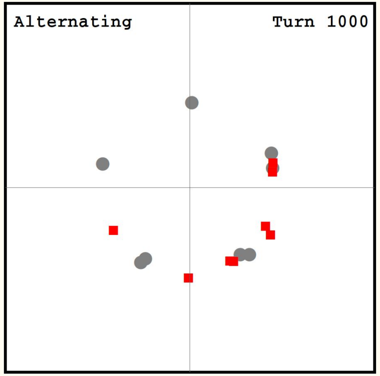


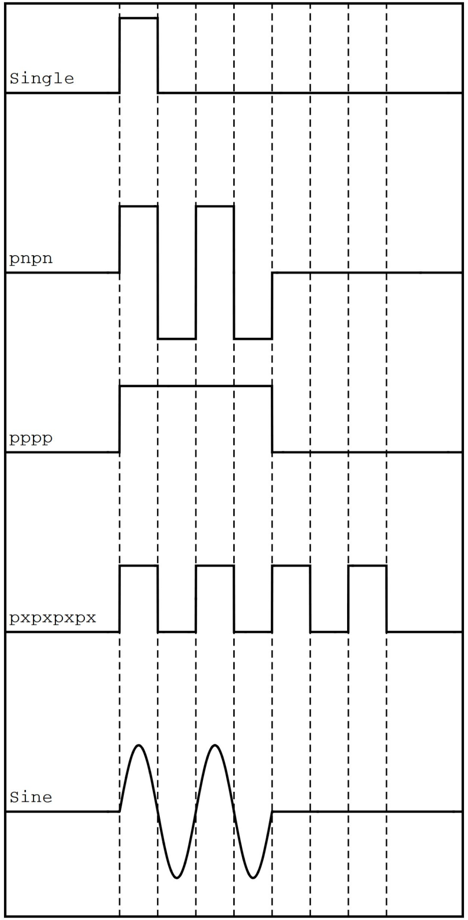


Pulsed quadrupoles

- Important to avoid complete attenuation
- Sequence of quadrupole kicks
    - Coincides with beam phase advance
    - Each kick amplifies the next
- Tighter “clumping” in phase space

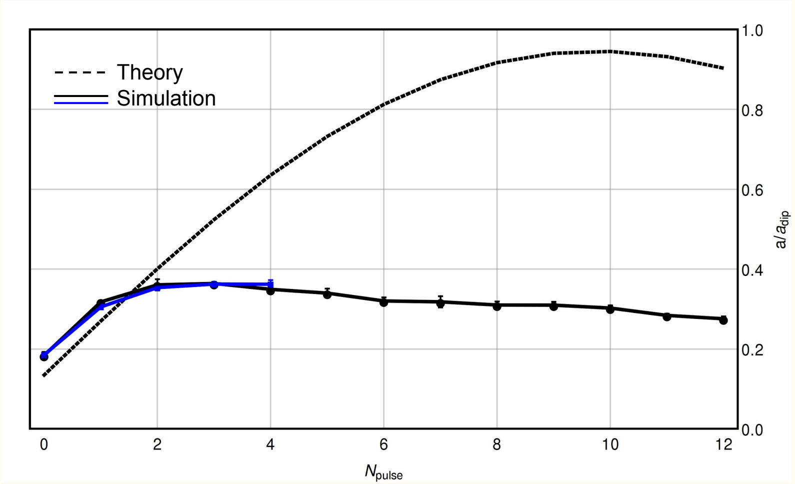






Pulsed quadrupoles (cont'd)

- Highly effective in boosting echo amplitude
  - Up to saturation point



Pulsed quadrupoles (cont'd)

- Highly effective in boosting echo amplitude
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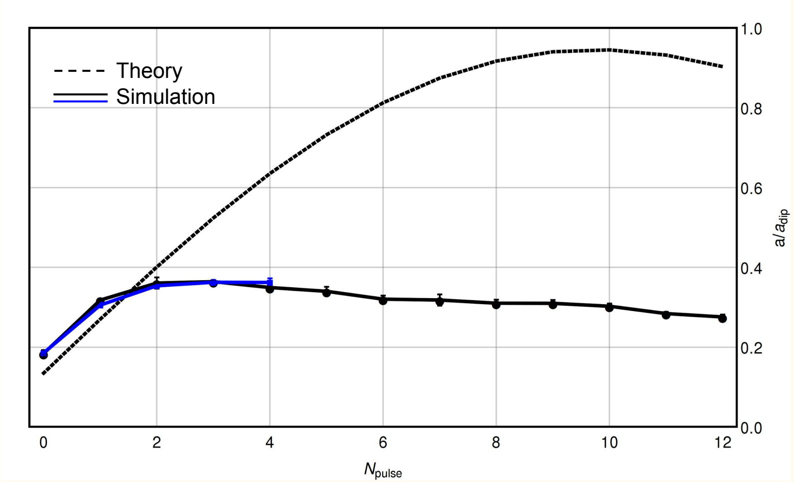
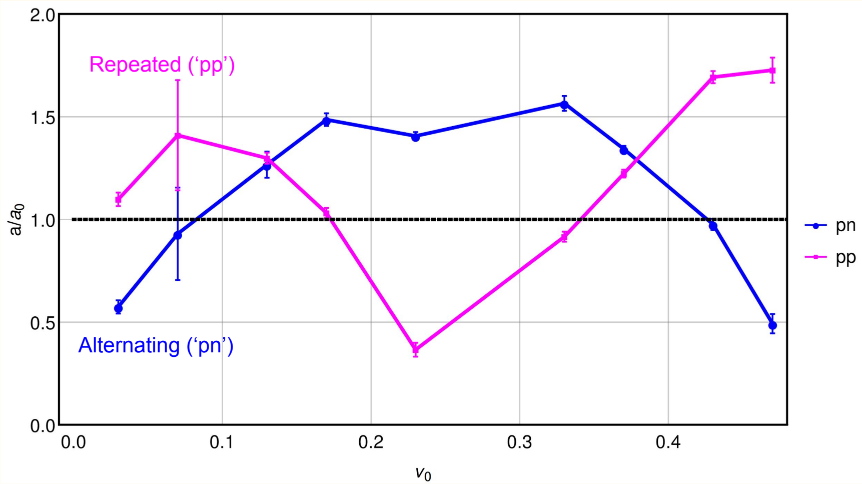
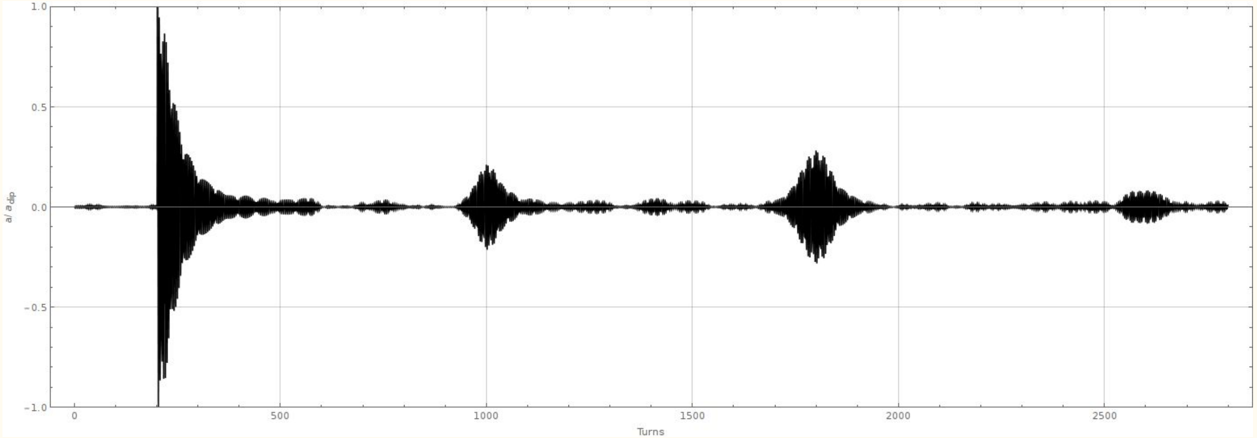
- Optimal sequence dependent on fractional tune





Pulsed quadrupoles (cont'd)

- Amplification of multiple echoes
- Apply quad kicks at τ and 2τ

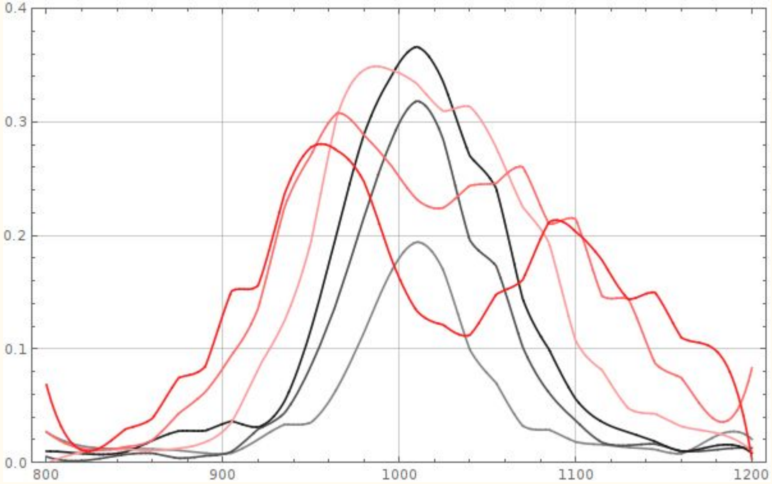


Conclusion

- Self-consistent measurement of D_1 coefficient using τ_{max}
- Pulsed quadrupole sequences as an effective means to boost echo amplitude
- Optimal pulse sequence dependent on fractional tune
- No need for alternating quadrupoles - sequences of single polarity can be just as effective
- Amplification of multiple echoes also possible

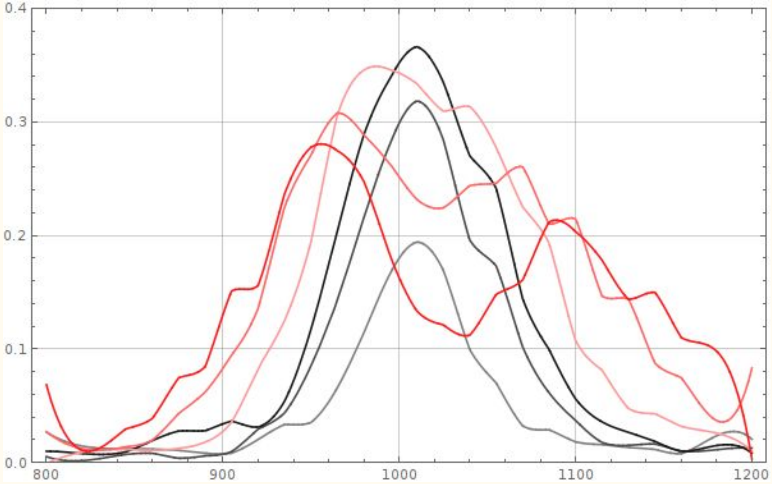
Future work

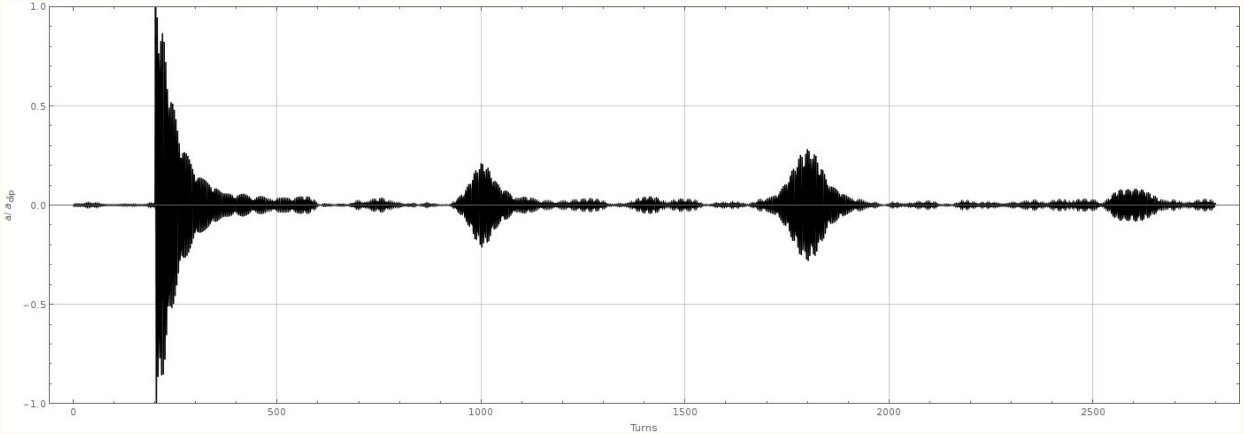
- Breaking the saturation limit (A≈0.4)



Future work

- Breaking the saturation limit (A≈0.4)
- Exploring novel pulse sequences
  - Boosting multiple echoes





Future work

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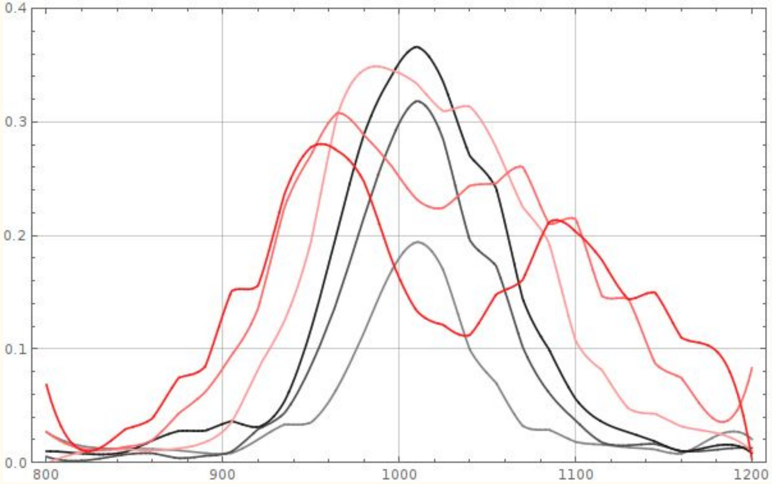
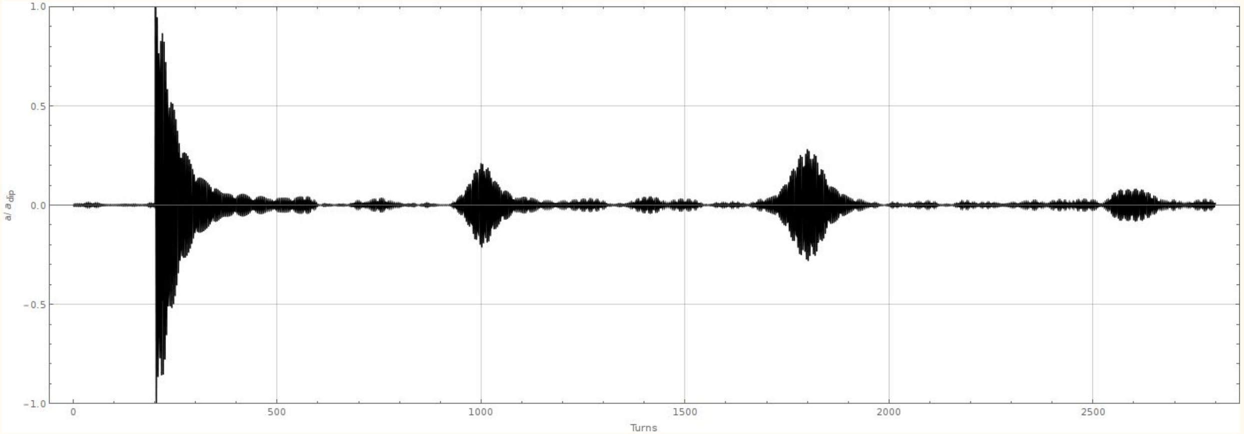
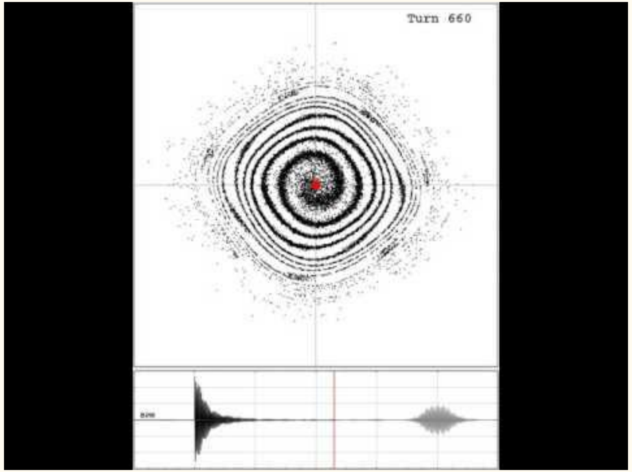
- Exploring novel pulse sequences
  - Boosting multiple echoes
- Extending simulation to 2D
  - Effect of coupling
- Specific to IOTA





Q&A



Video: https://youtu.be/l54tM4MBEVI

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